

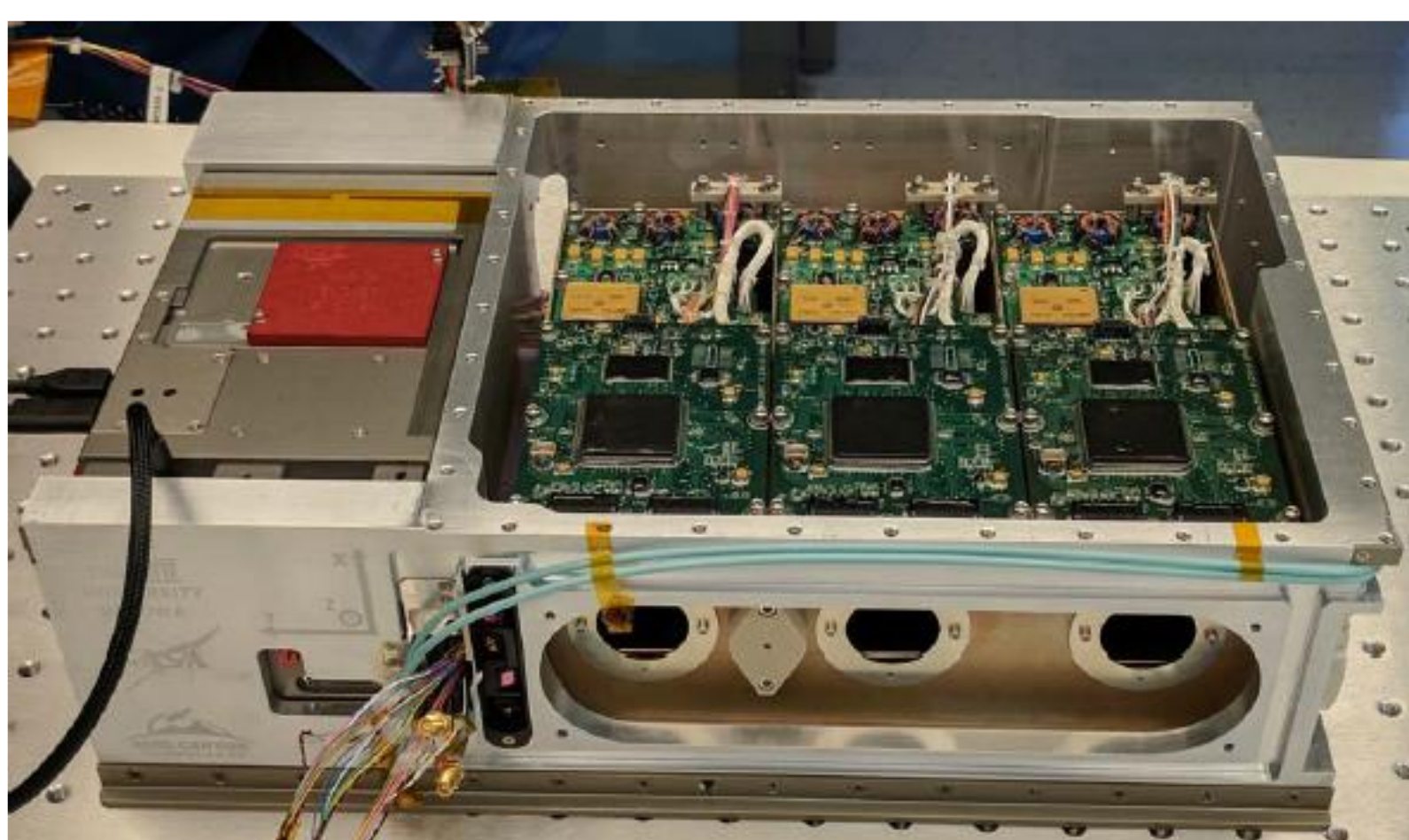
# HaloSat – A CubeSat that Studied the Hot Galactic Halo

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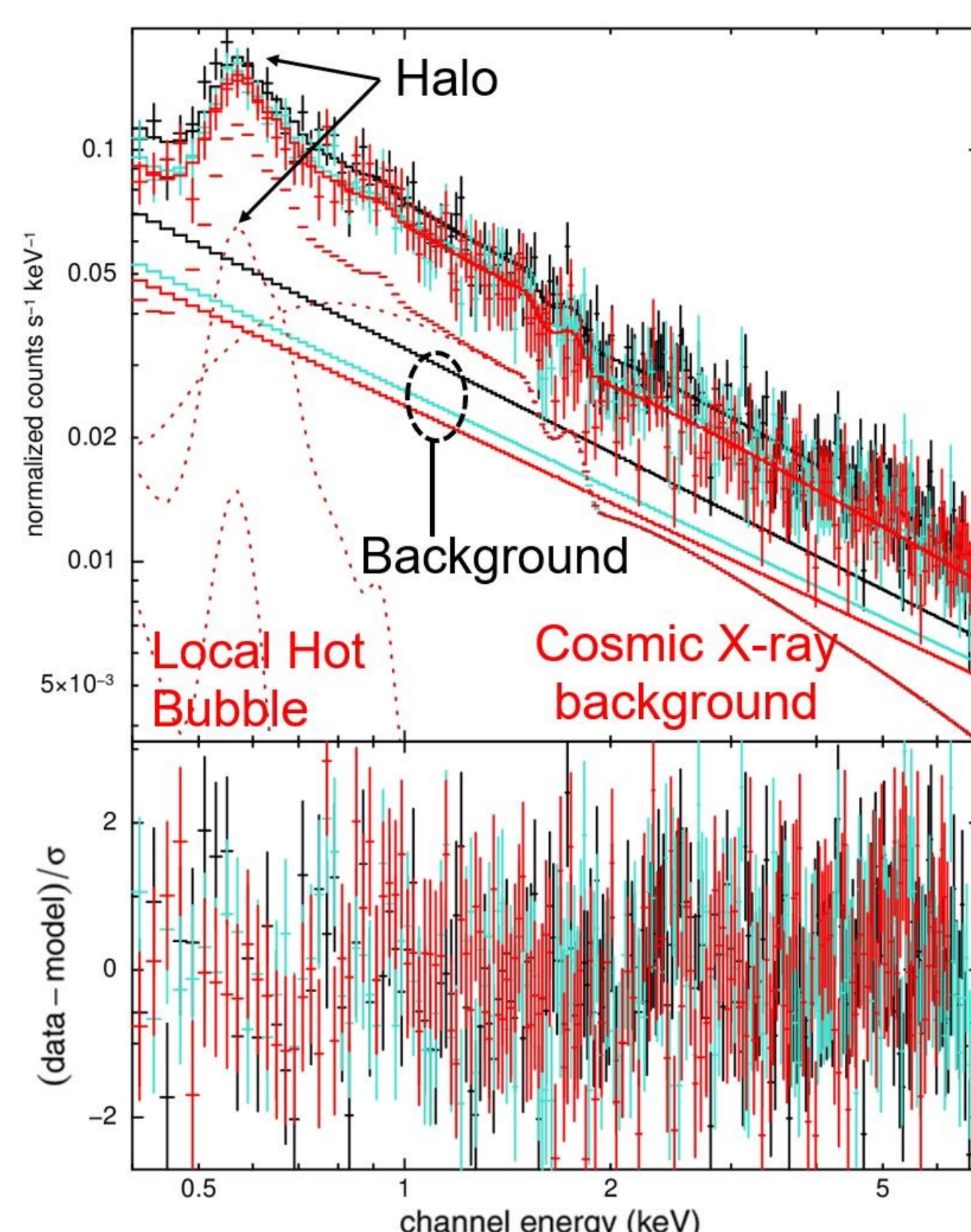


## HaloSat

HaloSat was the first CubeSat competitively funded by NASA's Astrophysics Division. HaloSat surveyed the sky in the soft (0.4-2 keV) band with the goal of studying diffuse X-ray emission from highly ionized oxygen in the circumgalactic medium (CGM) of the Milky Way (MW).



The HaloSat science instrument (shown above) contained three nominally identical X-ray detectors. The field of view had full response over a  $10^\circ$  diameter, tapering to zero response at  $14^\circ$  diameter. The detectors were sensitive in the 0.4-7 keV band. Typical halo spectra are shown below.



The figure of merit for observing diffuse emission, survey grasp, is the product of effective area and solid angle of the field of view,  $A\Omega$ . HaloSat has a small effective area, but a large field of view, giving it a grasp competitive with major missions. HaloSat's grasp ( $17.6 \text{ cm}^2 \text{ deg}^2$  at 600 eV) was larger than Chandra's at launch ( $8.7 \text{ cm}^2 \text{ deg}^2$ ).

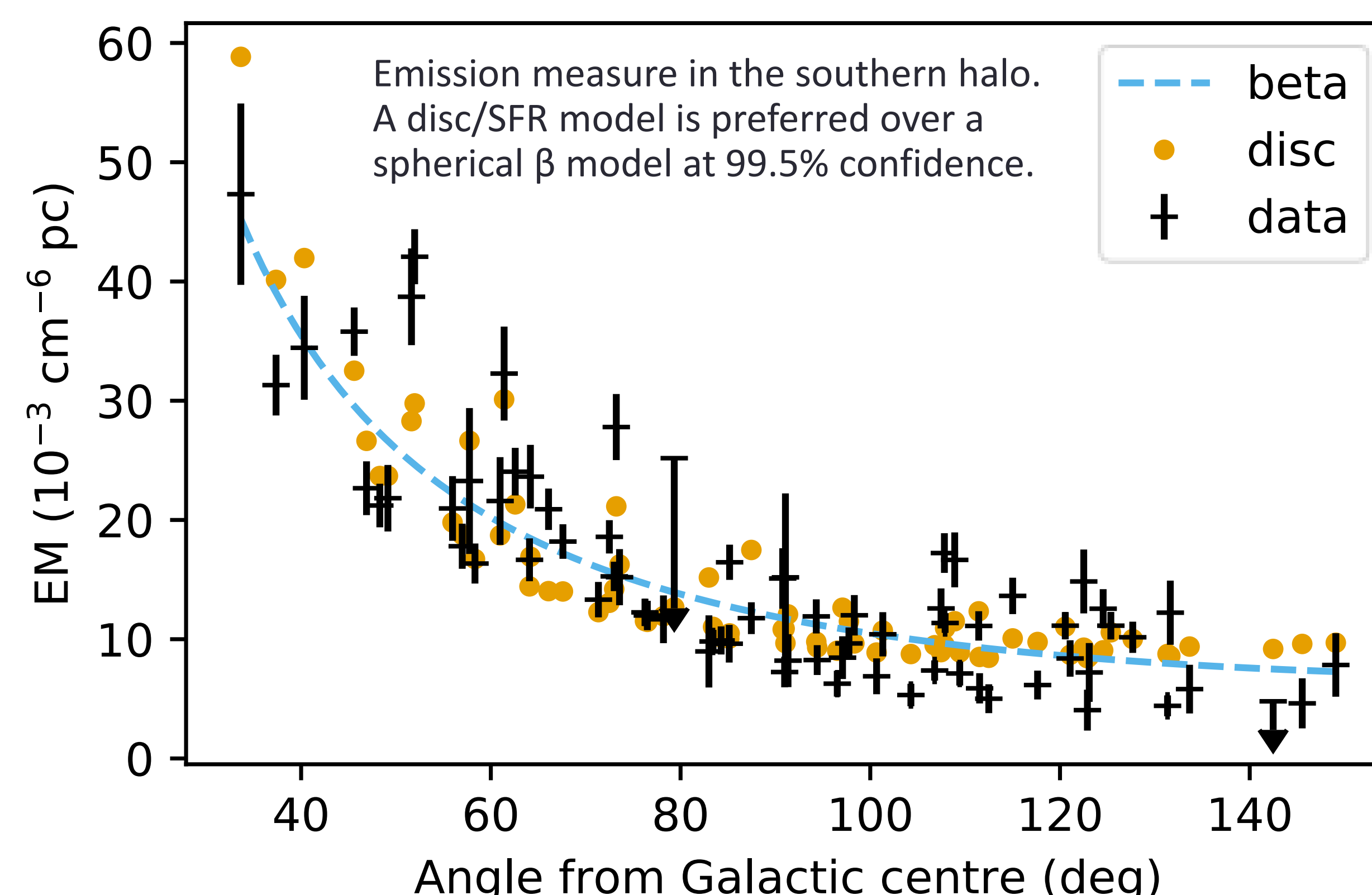
HaloSat data are archived at the HEASARC by a collaboration between NASA/MSFC, UI, and GSFC. See poster 104.01 by Jesse Bluem for details. HaloSat was built and operated by the University of Iowa (UI), NASA/GSFC, Johns Hopkins University, the Laboratoire Atmosphères, Observations Spatiales (LATMOS), and Blue Canyon Technologies.

## Results on the Halo/CGM

HaloSat's primary findings are that:

- X-ray emission from the MW CGM is clumpy with factor  $10\times$  variations on scales of tens of degrees.
- The X-ray emission is correlated with the surface density of the star formation rate (SFR) in the disk (see the figure to the right).
- Model fitting indicates a scale height of 1-2 kpc.
- Gas at two different temperatures ( $\sim 0.2 \text{ keV}$  and  $\sim 0.7 \text{ keV}$ ) is present. This may represent a continuous distribution of temperatures.

These results suggest that soft X-ray emission from the CGM is dominated by feedback from star formation and possibly nuclear activity.



## Other Results

The all-sky survey enabled science beyond studies of the halo, such as “The Orion OB Association as a Generator for the Hot Circumgalactic Medium” by Chase Fuller (talk #302.03). HaloSat's large field of view was key to observing the extent of the Orion-Eridanus superbubble in order to characterize the hot gas content and its variation with distance from the Orion star cluster. The results indicate that star-forming regions may energize the CGM.

HaloSat data have been used to study several extended soft X-ray sources including the North Polar Spur/Fermi Bubbles, the Cygnus Superbubble, and the Large Magellanic Cloud. HaloSat data have also been used for other studies such as a search for 3.5 keV line emission from a putative sterile neutrino. A list of HaloSat papers is given below.

### HaloSat publications (Student authors are marked in bold, early career authors are marked in italics.)

- “HaloSat: A CubeSat to Study the Hot Galactic Halo”, Kaaret, P., *Zajczyk, A., LaRocca, D.M., Ringuette, R., Bluem, J., Fuelberth, W., Gulick, H., Jahoda, K., Johnson, T.E., Kirchner, D.L., Koutroumpa, D., Kuntz, K.D., McCurdy, R., Miles, D.M., Robison, W.T., Silich, E.M., *Astrophys. J.*, 884, 162 (2019).*
- “Design and construction of the x-ray instrumentation onboard the HaloSat CubeSat”, **LaRocca, D.M.**, Kaaret, P., Kirchner, D.L., *Zajczyk, A., Robison, W., Johnson, T.E., Jahoda, K.M., Fuelberth, W., Gulick, H.C., McCurdy, R., White, K., Miles, D.M., *J. Astron. Telesc. Instrum. Syst.*, 6, 014003 (2020).*
- “Global X-Ray Properties of the Vela and Puppis A Supernova Remnants”, **Silich, E. M.**, Kaaret, P., *Zajczyk, A., LaRocca, D. M., Bluem, J., Ringuette, R., Jahoda, K., Kuntz, K. D., *Astron. J.*, 160, 20 (2020).*
- “On-ground calibration of the HaloSat science instrument”, *Zajczyk, A., Kaaret, P., LaRocca, D., Fuelberth, W., Gulick, H.C., Jahoda, K., Kirchner, D.L., McCurdy, R., Robison, W.T., Silich, E., *J. Astron. Telesc. Instrum. Syst.*, 6, 044005 (2020).*
- “A disk-dominated and clumpy circumgalactic medium of the Milky Way seen in X-ray emission”, Kaaret, P., Koutroumpa, D., Kuntz, K. D., Jahoda, K., **Bluem, J., Gulick, H., Hodges-Kluck, E., LaRocca, D. M., Ringuette, R., Zajczyk, A., *Nature Astron.*, 4, 1072-1077 (2020).**
- “An Analysis of the North Polar Spur Using HaloSat”, **LaRocca, D.M.**, Kaaret, P., Kuntz, K.D., Hodges-Kluck, E., *Zajczyk, A., Bluem, J., Ringuette, R., Jahoda, K.M., *Astrophys. J.*, 904, 54 (2020).*
- “A HaloSat Analysis of the Cygnus Superbubble”, **Bluem, J.**, Kaaret, P., **Fuelberth, W., Zajczyk, A., LaRocca, D.M., Ringuette, R., Jahoda, K.M., Kuntz, K.D., *Astrophys. J.*, 905, 91 (2020).**
- “Total X-Ray Emission from the LMC Observed with HaloSat”, **Gulick, H.**, Kaaret, P., *Zajczyk, A., LaRocca, D.M., Bluem, J., Ringuette, R., Jahoda, K., Kuntz, K.D., *Astron. J.*, 161, 57 (2021).*
- “A Search for the 3.5 keV Line from the Milky Way's Dark Matter Halo with HaloSat”, **Silich, E.M.**, Jahoda, K., Angelini, L., Kaaret, P., *Zajczyk, A., LaRocca, D.M., Ringuette, R., Richardson, J., *Astrophys. J.*, 916, 2 (2021).*
- “HaloSat Observation of the Virgo Intracluster Medium”, **Hewitt, N.H.**, Kaaret, P., **Fuller, C., *Res. Notes AAS*, 5, 185 (2021).**
- “HaloSat Observations of Heliospheric Solar Wind Charge Exchange”, *Ringuette, R., Koutroumpa, D., Kuntz, K. D., Kaaret, P., Jahoda, K., LaRocca, D., Kounkel, M., Richardson, J., Zajczyk, A., Bluem, J., *Astrophys. J.*, 918, 41 (2021).*
- “Widespread Detection of Two Components in the Hot Circumgalactic Medium of the Milky Way”, **Bluem, J.**, Kaaret, P., Kuntz, K. D., Jahoda, K., Koutroumpa, D., Hodges-Kluck, E.J., **Fuller, C.A., LaRocca, D.M., Zajczyk, A., *Astrophys. J.*, 936, 17 (2022).**
- “The Orion OB Association as a Generator for the Hot Circumgalactic Medium”, **Fuller, C.**, Kaaret, P., **Bluem, J., Kuntz, K. D., Hodges-Kluck, E.J., Jahoda, K., *Astrophys. J.*, 943, 61 (2023).**